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Design and Field Demonstration of a Low-NOx Burner for TEOR (Thermally Enhanced Oil Recovery) Steamers

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16. ABSTRACT The paper discusses a program that addresses the need for advanced NOx control technology for thermally enhanced oil recovery (TEOR) steam generators. A full-scale (60 million Btu/hr) burner system has been developed and tested, the concept for which was based on fundamental studies. Test results are included for full-scale burner performance in an experimental test furnace, and in a field-operating steam generator which was subsequently retrofitted in a Kern County, California, oilfield. (NOTE: NOx control techniques including low-NOx burners, postflame NH3 injection, or other postflame treatment methods--e.g., selective catalytic reduction--have been considered in order to comply with regulations. The level of NOx control required to meet both growth and air quality goals has typically been difficult to achieve with available technology while maintaining acceptable CO and particulate emissions as well as practical flame conditions within the steamer.)

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Introduction

Enhanced oil recovery processes are applied to oil field production in order to extract heavy, viscous crude oil and tar sands which cannot otherwise be produced. A significant fraction of total U.S. oil reserves require application of enhanced oil recovery in order to be realized. Thermally enhanced oil recovery (TEOR) involves injection of wet steam which is typically produced by combusting crude oil in oil field steam generators ranging in size from 7 to 15 MW capacity. More than 90 percent of all oil field steam generators in the United States are located in California, approximately one-third of which are located in Kern County. Approximately one-third of the produced crude oil is consumed by the steam generator, amounting to over 200,000 barrels of crude oil consumed per day at full capacity.

The crude oils which are fired in these steam generators are typically high in nitrogen (0.8 to 1.0 percent) and sulfur content. Combustion of these fuels leads to high levels of NO_x and SO_x emissions unless preventive measures are taken. The contribution of fuel-bound nitrogen to NO_x emissions from fuel oil combustion is well documented (1,2). A survey of conventional TEOR steam generators in Kern County (3) showed that uncontrolled NO_x emissions ranged from 160 to 825 ppmv (corrected to 3 percent oxygen), depending on operating conditions and design variables, with an average emission level of approximately 325 ppm at an average excess oxygen level of 4.5 percent. These high emission levels and deteriorating air quality have prompted state and local legislation regulating NO_x emissions from TEOR steam generators, which threatens to limit oil production unless NO_x control methods are applied. For certain new or modified stationary sources (including TEOR steam generators) these regulations require application of the Best Available Control Technology (BACT) or the Lowest Achievable Emission Rate (LAER) to control the emission of any air containment or precurser for which there is a national ambient air quality standard (including NO_2). Additionally, NO_x emissions from all steam generators are currently limited to 0.3 $lb/10^6$ Btu (about 225 ppm, corrected to 3 percent oxygen). Further reductions to 0.25 and to 0.14 $lb/10^6$ Btu (about 190 and 105 ppm) may be required if ambient NO_2 concentrations exceed certain trigger levels. NO_x control techniques including low NO_x burners, postflame NH_3 injection, or other postflame treatment methods (e.g. selective catalytic reduction) have been considered in order to comply with regulations. Enhanced oil recovery operations are projected to expand in Kern County through 1995. The level of NO_x control required to meet both growth and air quality goals has typically been difficult to achieve with available technology while maintaining acceptable carbon monoxide and particulate emissions as well as practical flame conditions within the steamer.

This paper discusses a program which addresses the need for advanced NO_x control technology for oilfield steam generators. A full-scale (60×10^6 Btu /hr) burner system has been developed and tested, the concept for which was based on fundamental studies. Test results are included for full-scale burner performance in an experimental test furnace, and in a field-operating steam generator which was subsequently retrofitted in the Kern Front oilfield.

Concept Development

Combustion-generated NO_x emissions can be reduced by combustion modification techniques which involve staging the heat release process. Techniques such as flue gas recirculation strive to control NO formed from molecular nitrogen (thermal NO) by suppressing peak flame temperatures, and are only partially effective with nitrogen-containing fuels (4). NO formation from nitrogen in the fuel (fuel NO) is very sensitive to reactant stoichiometry, and can be significantly reduced by initially burning the fuel under fuel-rich conditions. Staged combustion, therefore, involves creating a fuel-rich zone to promote formation of molecular nitrogen from the nitrogen species (HCN, NH_3, NO) evolved as the liquid fuel decomposes, followed by a fuel-lean zone optimized for minimum NO formation.

The mechanisms controlling NO_x formation during staged combustion were identified in a previous study (5) for liquid fuels ranging from distillate oil to residual oil to alternative coal- and shale-derived oils. The key parameters were first-stage stoichiometry, thermal environment, and residence time. NO_x was relatively insensitive to second (burnout) stage parameters. These bench-scale studies showed that, under optimum staged conditions, NO_x emissions below 100 ppm were possible and were independent of fuel nitrogen content.

Based on the results of the bench-scale studies, prototype combustors were designed and tested at 2×10^6 Btu/hr and 10×10^6 Btu/hr (6) to further develop scaling criteria for the design of a full-scale (60×10^6 Btu/hr) burner. These pilot-scale tests confirmed that a staged combustion system could be designed and scaled over a 150:1 range which is capable of achieving less than 85 ppm NO (at 3% O_2) firing high-nitrogen residual oil, with low CO and smoke emissions.

Burner Design

Figure 1 illustrates the design of the full-scale burner. Optimization of both the fuel-rich and fuel-lean stages is achieved utilizing a physically separate first-stage chamber. The first-stage chamber is formed by a horizontal cylinder which is refractory lined and recuperatively cooled in order to maintain first-stage temperature; the exterior of the chamber is also insulated to prevent heat loss to the surroundings. The recuperative design reduces thermal inertia and thermal stresses developed during transient (start-up and shutdown) operation by employing a relatively thin layer of refractory. Substantial primary air preheat is developed which enhances fuel vaporization near the fuel injector.

A commercial air register, ignitor, and fuel gun are used in the primary ignition zone. The atomizer is a twin-fluid internal mixing atomizer using steam for atomization. Primary throat diameter was scaled up from the pilot-scale burners on the basis of constant velocity. The exit diameter of the chamber is reduced to provide a first stage exit velocity of approximately 50 feet per second while reducing radiative heat losses from the first stage.

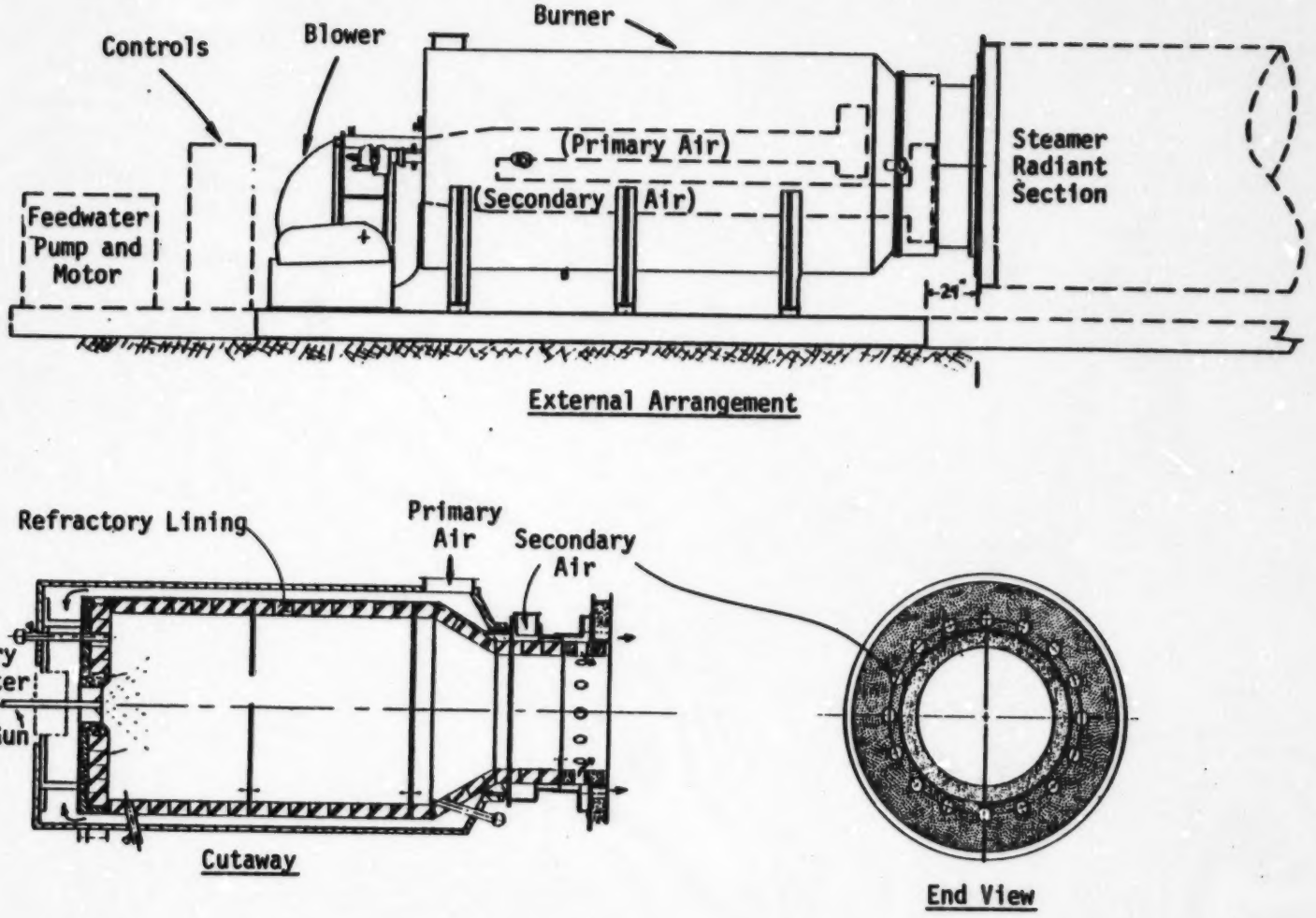

Figure 1. Full-scale (60 x 10^6 Btu/hr) low-NO_x burner design.

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Secondary air is admitted at the chamber exit through discrete ports oriented parallel to and normal to the burner axis. The distribution of secondary air can be varied to provide some degree of control over second stage mixing. Testing on the bench-scale and small pilot-scale systems had shown that emissions were insensitive to second-stage mixing and excess oxygen level; however, at 10 x 10^6 Btu/hr, results suggested that these parameters may have greater influence on emissions and flame shape in larger systems.

The burner is equipped with a hybrid electro-pneumatic control system for normal ignition sequences and load modulation. A programmable controller serves to control first-stage stoichiometric ratio and second-stage excess oxygen level for minimum NO_x emissions. The hybrid approach was selected for the reliability and easy field maintenance of a pneumatic system plus the flexibility and more precise control possible with a programmable electronic controller.

Full-Scale Evaluation

Full-scale burner performance was characterized in two phases. The first phase was conducted in an experimental test furnace designed to simulate the thermal environment of a watertube boiler furnace. The second phase was conducted in a conventional TEOR steam generator located in the Kern County oilfields.

The objectives of the initial series of tests were to cure the refractory lining under controlled conditions firing natural gas, and to optimize burner parameters for emissions and flame shape without risk to field equipment. Shakedown of the mechanical and control systems was dovetailed into this preliminary test series.

The experimental test furnace used in the preliminary evaluation of the burner is illustrated in Figure 2. The furnace consists of a horizontal cylinder which is externally cooled by water sprays. Part of the internal surface (approximately 60 percent) is lined with refractory to approximately simulate the thermal environment of a watertube boiler. The burner is mounted on one end of the cylinder and combustion products exhaust on the opposite end.

The furnace exhaust passes through a long stack to a scrubbing tower for particulate control. A sampling station is located near the exhaust stack upstream of the scrubbing tower. Exhaust samples were withdrawn from the stack using a water-cooled stainless steel probe, dried in an ice-bath condenser and pumped to the control room and analyzer equipment. Continuous analyzers were used for measurement of O_2, CO, CO_2, and NO_x. Smoke number was manually determined using a Baccarach Smoke Spot pump. Gas temperatures were measured using suction pyrometers.

Table I compares the characteristics of the experimental test furnace and the field steam generator. The test furnace is 1.5 m (5 ft) larger in

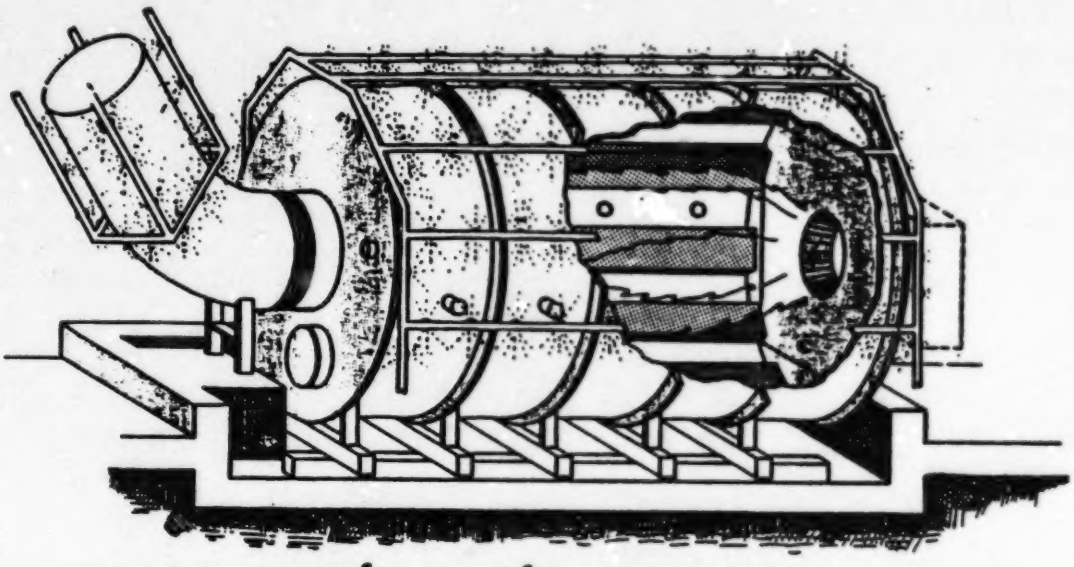

Figure 2. 50×10^6 - 80×10^6 Btu/hr experimental test furnace.

Table I. Comparison of furnace characteristics.

PARAMETER		EXPERIMENTAL FURNACE	TEOR STEAM GENERATOR
Firing			
Configuration		Single Wall	Single Wall
Capacity	Maximum	23 MW (80 x 10^6 Btu/hr)	16.3 MW (55.8 x 10^6 Btu/hr)
	Minimum	9 MW (30 x 10^6 Btu/hr)	4.1 MW (14.1 x 10^6 Btu/hr)
Dimensions			
Shape		Horizontal Cylinder	Horizontal Cylinder
Diameter		4.3 m (14 ft.)	2.7 m (9 ft.)
Length		6.4 m (12 ft.)	11 m (35 ft.)
Volume		87 m^3 (3079 ft^3)	76 m^3 (2700 ft^3)
Surface Area	Cooled	44 m^2 (475 ft^2)	-
	Insulated	66 m^2 (713 ft^2)	-
	Total	110 m^2 (1188 ft^2)	-
Thermal Environment*			
Cooling		Water Sprays on Exterior Surfaces	Steam Tubes
Exit Temperature		1150°C (2100°F)	980°C (1800°F)
Heat Release/Cooled Surface		0.37 MW/m^2 (117,474 Btu/hr ft^2)	0.09 MW/m^2 (28,000 Btu/hr ft^2)
Heat Release/Volume		0.19 MW/m^3 (18,100 Btu/hr ft^3)	0.21 MW/m^3 (21,000 Btu/hr ft^3)
Radiant Zone Heat Flux		0.19 MW/m^2 (58,810 Btu/hr ft^2)	0.05 MW/m^2 (16,000 Btu/hr ft^2)
Furnace Efficiency		50%	58%

* Based on 16.3 MW Thermal Input

diameter, 4.6 m (23 ft) shorter in length than the field steam generator, and the test furnace volume is 14 percent greater. Measured gas temperature at the test furnace exit is slightly hotter than typical TEOR steam generator radiant section exit gas temperatures. The overall thermal environment is similar in terms of volumetric heat release and furnace efficiency. (Surface heat flux calculations for the test furnace and steam generator are not directly comparable since only that portion of the furnace surface not covered by refractory is considered as cooled surface.)

The preliminary emissions testing was conducted firing a residual fuel oil derived from California crude oil. The properties of this oil and the crude oil later used in the field evaluation are shown in Table II. Properties of the two oils are similar with the exception of viscosity, which is much higher for the crude oil than for the residual oil. Nitrogen content of the residual oil is high (0.74 wt %) and compares favorably with that of the crude oil (0.83 wt %).

Test Furnace Results

Typical emissions from the full-scale burner are illustrated in Figure 3 as a function of first stage stoichiometric ratio for two primary throat configurations. Excess oxygen was held constant at 3 percent (dry basis). A sharp minimum in NO emissions occurred as first-stage stoichiometry was decreased. This is consistent with previous results at bench and pilot scale, and has been shown to occur due to a tradeoff between increasing formation of reduced nitrogen species and decreasing NO formation in the first-stage as stoichiometry decreases (5). Minimum NO emissions ranged from 50 to 58 ppm at 55 x 10^6 Btu/hr. (All volumetric pollutant emission levels throughout this paper are corrected for dilution to 3 percent oxygen.) Smoke and CO emissions were essentially insensitive to first-stage stoichiometry and remained at low levels over the range of conditions shown.

The effect of adding a conical oil gun diffuser to the primary throat is also shown in Figure 3. The diffuser was added to improve flame stability during start-up. Addition of the diffuser produced a slight increase in NO emissions (from 50 to 58 ppm) and shifted the optimum stoichiometric ratio from 0.59 to 0.62. This is due to a change in the distribution of residence times and local stoichiometries caused by the different mixing patterns produced with the diffuser. CO emissions were lower with the diffuser; however, smoke emissions were slightly higher.

Another key burner performance parameter is flame shape. The radiant furnace of TEOR steam generators has a high length/diameter ratio, and flame impingement on the walls of the furnace can cause rapid degradation of tube hangers and furnace insulation. Pilot-scale studies (6) had shown that flame shape could be varied by changing secondary mixing characteristics, at the risk of increasing NO_x emissions. Figure 4 shows sketches of the secondary flame shape obtained for two different modes of secondary air injection in the test furnace. All the secondary air was injected through ports parallel to the axis of the burner, and the number of open ports (hence velocity)

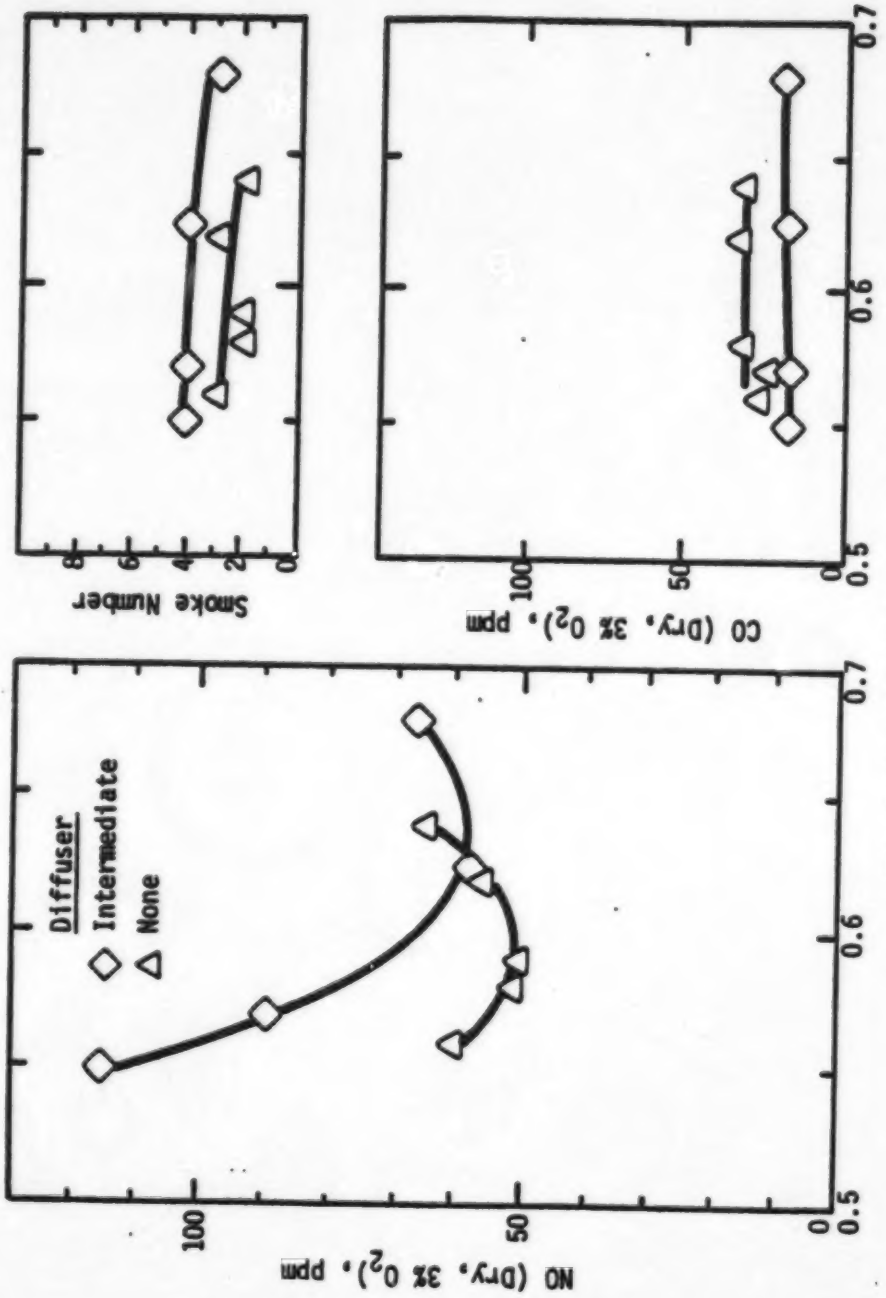

Figure 3. Test furnace results: Effect of first-stage stoichiometry and mixing on emissions (55×10^6 Btu/hr, 3 percent excess O_2).

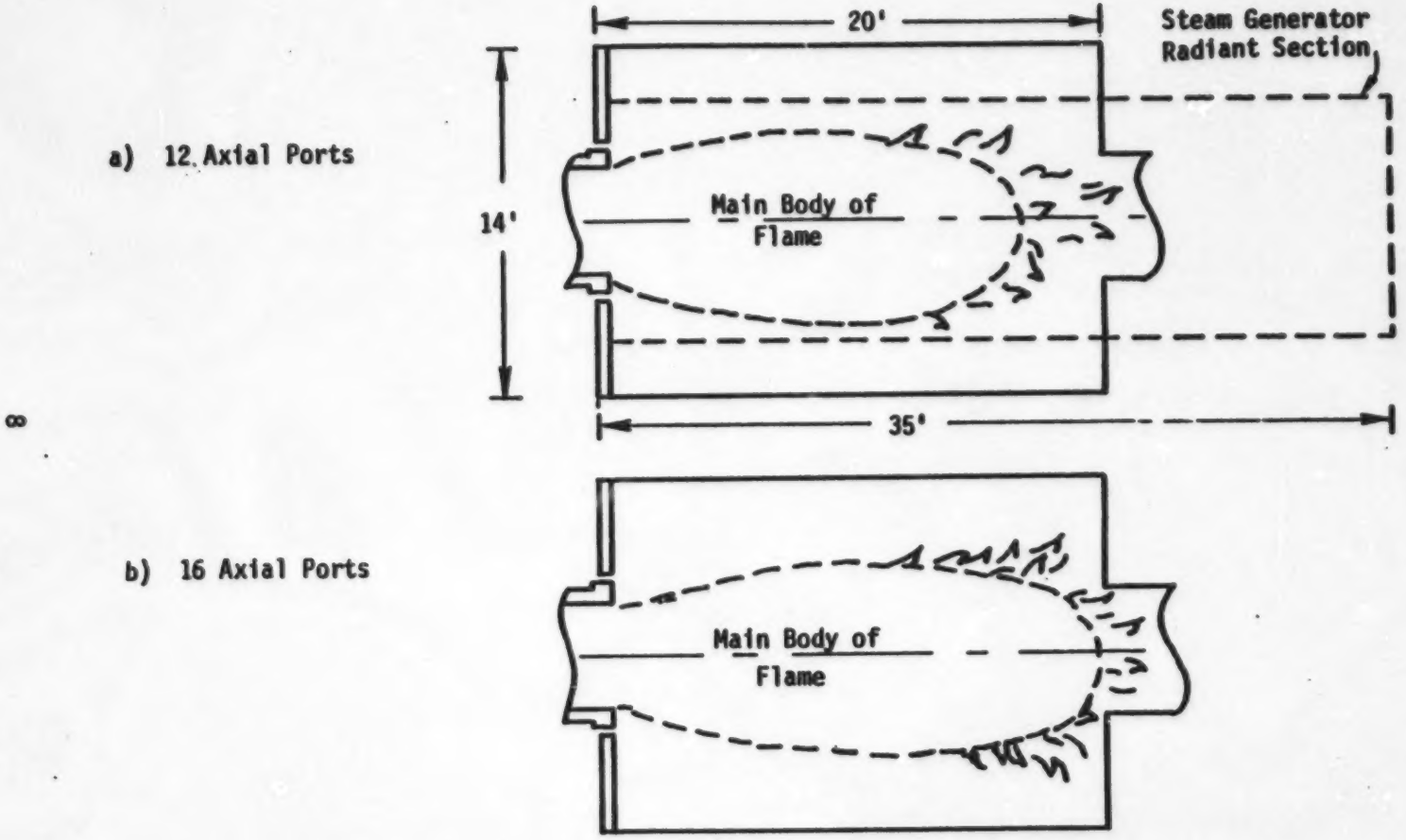

Figure 4. Test furnace results: Effect of secondary air injection on flame shape.

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Table II. Properties of residual and crude oils used in full-scale burner evaluation.

	California Residual Oil	Kern Front Crude Oil
Ultimate Analysis (wt %)		
Carbon	85.07	85.42
Hydrogen	11.30	10.88
Nitrogen	0.74	0.83
Sulfur	1.37	1.05
Ash	0.03	0.03
Oxygen (by difference)	1.49	1.79
	100.00	100.00
Specific Gravity (@ 15°C)	0.974	0.978
API Gravitry (@ 60°F)	13.8	13.2
Viscosity		
SSU @ 140°F	933	2,450
cp @ 60°C	197	518
SSU @ 210°F	139	274
cp @ 99°C	29	58
Heat of Combustion		
Btu/lb, Gross	18,357	18,310
Net	17,326	--
kJ/g, Gross	42.7	42.6
Net	40.3	--

was varied. The flame extended to the rear wall and into the exhaust duct of the test furnace (approximately 20 ft) when all 16 axial ports were open and was approximately 7 ft in diameter. Decreasing the number of open ports to 12 increased secondary air velocity by approximately 80 percent and produced a flame which was slightly wider and approximately 18 feet in length.

Minimum NO_x levels were not strongly sensitive to secondary air port configuration (Figure 5). Optimum stoichiometric ratio ranged from 0.63 to 0.65 with the 12 and 16 port configurations; however, with 8 ports the optimum shifted to 0.57. Smoke and CO emissions were insensitive to secondary air injection configuration for the conditions illustrated in the figure.

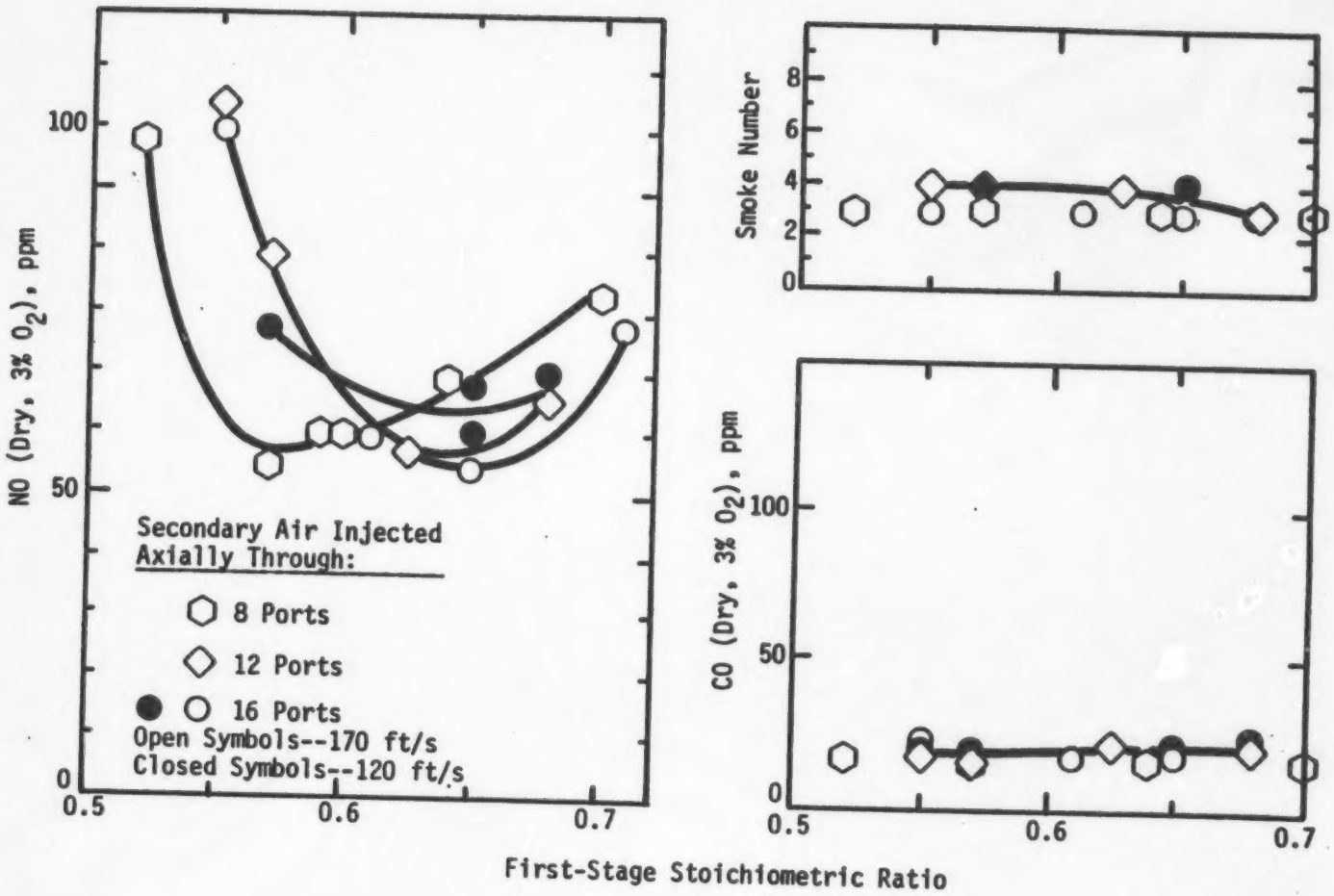


Figure 5. Test furnace results: Effect of number and velocity of secondary air jets on emissions (55×10^6 Btu/hr, 3% excess O_2).

Other parameters which were optimized during the test furnace trials included atomizer pressure and spray angle, primary swirl level, and settings for start-up and shutdown. At completion of these tests, 131 hours of operation had been achieved. The burner was then transported to the host steam generator site in Kern County, California.

Field Retrofit

The retrofit task of the demonstration program involved selecting an existing steam generator typical of those currently in operation to host the demonstration, transportation of the burner to the host site, removal of the existing burner hardware, and installation of the prototype burner hardware and controls. TEOR steam generators are relatively simple in construction compared to boilers and utilize a single-pass, drumless design. The radiant section is formed by a horizontal, refractory-lined steel cylinder, with the burner mounted on one end and an exhaust transition leading to a convective economizer section on the other end. Steaming tubes extend axially and are supported near the refractory on tube hangers around the generator circumference. The entire unit with feedwater pump and controls is normally skid-mounted and shop-assembled and is shipped by rail car or truck to the installation site.

Retrofit installation of the low-NO_x burner onto the host steamer required replacing the refractory-faced front wall of the radiant section, lengthening the foundation and skid to accommodate the length of the burner, extension of plumbing and electrical wiring, and installation of supplementary controls (e.g. programmable controls, additional limit switches and relays, oxygen probe). Revised operating procedures to accommodate heatup and cooldown of the refractory lining were also developed. Following completion and shakedown of the retrofit, testing was initiated.

Field Test Results

The field testing of the steam generator was accomplished in three phases: (1) optimization, (2) detailed characterization, and (3) 30-day evaluation. At this writing the 30-day evaluation is still in progress and results are not yet available.

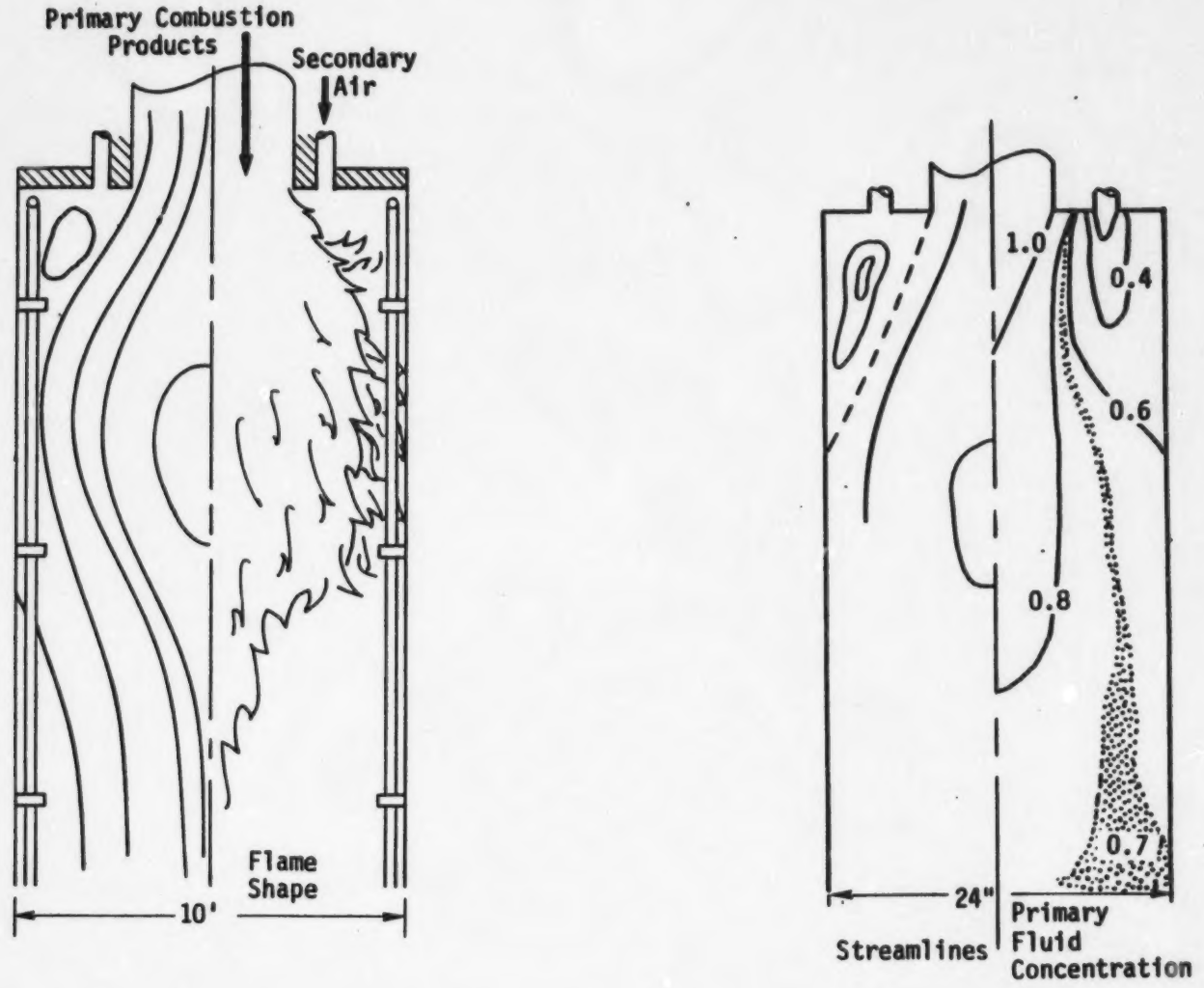
The purpose of the initial test series was to optimize the burner operating parameters to achieve safe start-up and shutdown, acceptable flame characteristics within the steam generator radiant section, and low NO, CO, and smoke emissions. The steam generator was gradually brought to full load on crude oil. Initial emissions measurements were consistent with results obtained in the test furnace. However, at full load, flame impingement on the walls of the radiant section close to the burner was encountered. The flame shape was much wider and shorter compared to that obtained in the test furnace, and this may be related to the smaller diameter of the steam generator.

The initial degree of control over secondary air injection was not sufficient to produce an acceptable flame and other modifications were considered. Although there is a considerable body of literature describing the behavior of confined, double-concentric jets in both nonreacting and flame environments, there is little information for highly confined systems similar to the present burner/furnace combination. The multijet method of secondary air addition also added another degree of uncertainty in attempting to design the optimum modification by classical methods. A very brief series of 1/5-scale, cold isothermal modeling tests were therefore conducted using an existing flow modeling facility in order to evaluate the potential effectiveness of the proposed modifications.

The hardware for the 1/5-scale model was geometrically scaled. Secondary air jet velocity was held constant while primary flowrate exit velocity was reduced to maintain the same momentum ratio as at full scale. Flow pattern visualization was achieved with plane illumination and injection of soap bubbles using a commercial neutral-buoyancy bubble generator. Mixing patterns were determined by tracer concentration measurements.

Figure 6 compares the flame and estimated flow patterns observed in the steamer, under full-load conditions, to the flow patterns and concentration profiles measured in the 1/5-scale model for the baseline configuration. The flow patterns in the model and full-scale steamer appeared to be similar, characterized by a strong external recirculation zone close to the burner exit, rapid expansion of the primary jet toward the wall, and a lazy central recirculation zone. The point at which the boundary of the primary streams reached the wall in the model corresponded approximately to the point where flame impingement had occurred in the actual steam generator. The apparent spreading angle of the primary jet boundary was approximately 20 degrees (half-angle). The model also indicated that primary fluid was rapidly entrained into the secondary jets and external recirculation zone very close to the burner, illustrated by the concentration profiles in Figure 6. The model appeared to reasonably simulate the phenomena observed in the actual steam generator for the baseline configuration.

Figure 7 illustrates model results for two of the modifications considered. The first modification (7b) involved decreasing the first-stage exit diameter. The diameter reduction increased the primary-to-secondary jet momentum ratio from 0.35 to 0.56. The resulting flow pattern showed that the point at which the primary jet reached the wall was moved 50 percent farther downstream, with an apparent spreading angle of 15 degrees. The intensity of the recirculation zone was somewhat reduced, and the central recirculation zone disappeared entirely. The mixing profiles indicated that the entrainment of primary fluid toward the walls near the burner was significantly reduced, although there was still significant mixing between the two streams farther downstream.



(a) Full-Scale Steam Generator

(b) Cold Isothermal Model

Figure 6. Comparison of observed flame shape in full-scale steam generator to mixing and flow pattern in cold isothermal model.

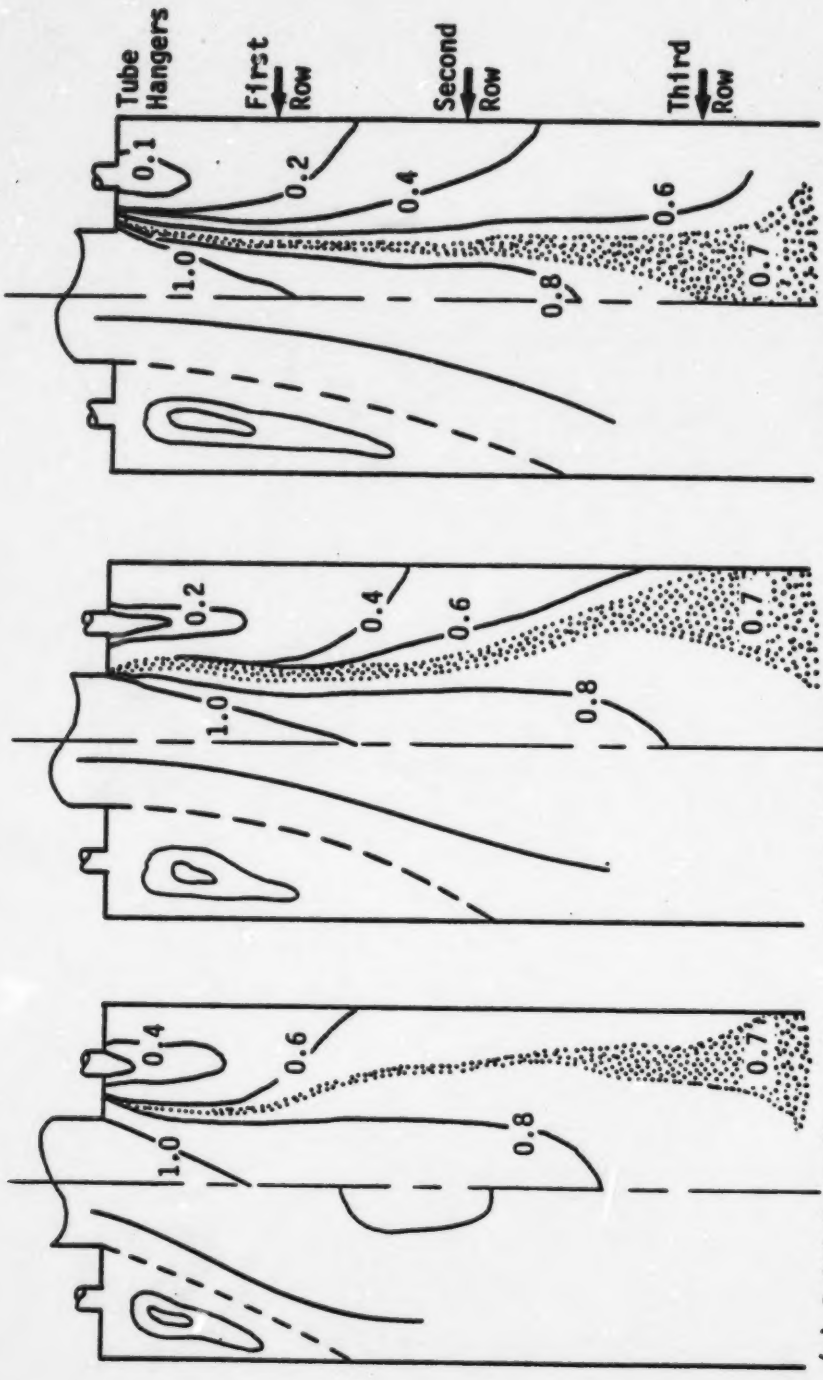


Figure 7. Effect of changing primary and secondary jet momentum on mixing and flow patterns in cold isothermal model.

A second field modification considered was to remove inserts from the axial secondary air ports to enlarge the port area, thereby reducing the momentum of the secondary jets to reduce the tendency of the jets to pump primary fluid toward the walls. Figure 7(c) illustrates the flow and mixing patterns obtained with both modifications simulated in the model. This combination resulted in a primary-to-secondary jet momentum ratio of 0.99. Reduction of the secondary jet momentum further reduced the apparent spreading angle of the primary fluid boundary to approximately 13 degrees, and further reduced the primary fluid concentration at the walls of the model near the burner. In spite of the delayed mixing between the streams near the burner, good mixing was still achieved at a distance approximately equivalent to the midpoint of the steam generator, as shown by the region of 0.7 primary fluid concentration. This concentration corresponds to the completely mixed concentration.

The model results suggested that the two modifications considered should provide a substantial improvement in flame pattern by delaying mixing between the two streams and by increasing the time for combustible mixtures to reach the furnace walls. The second modification offered greater assurance of eliminating flame impingement; however, there was some concern that complete downstream mixing would be difficult to achieve. It was decided to execute the modifications stepwise, starting with reduced primary exit diameter. This modification was executed, and the steam generator was again test-fired. No signs of flame impingement were observed. The flame was much narrower than the original flame and was generally shaped similar to the region outlined by the 0.6-0.7 isoconcentration profiles illustrated in Figure 7(b). Overall flame length was approximately 18 to 20 feet (between third and fourth row of tube hangers). The "tail" of the flame occasionally licked the steam tubes; however, this was considered minor and did not raise concern over tube or refractory life. Since the flame shape produced by the first modification was considered adequate, no attempts were made to further improve flame shape.

Figure 8 presents NO_x, CO, and smoke emissions from the steam generator firing at 54 x 10^6 Btu/hr after optimization of second-stage flame shape. Data are shown versus first-stage stoichiometric ratio for two excess oxygen levels. The fuel was Kern Front crude oil (Table 2). Minimum NO_x levels were between 55 and 65 ppm (corrected to 3 percent oxygen). CO and smoke emissions were also low at the optimum stoichiometry; however, below the optimum stoichiometry, smoke was slightly higher for 2 percent excess oxygen than for 3 percent. This behavior was attributed to second-stage mixing; however, since conditions below the optimum stoichiometry do not represent normal operation, no further optimization was required. NO_x and CO emissions were insensitive to excess oxygen. It should also be mentioned that the measured CO emissions were near the detection limit of the continuous (nondispersive infrared) analyzer and may represent interference by CO_2. Measurements of CO by gas chromatography indicated that true levels were below 1 ppm.

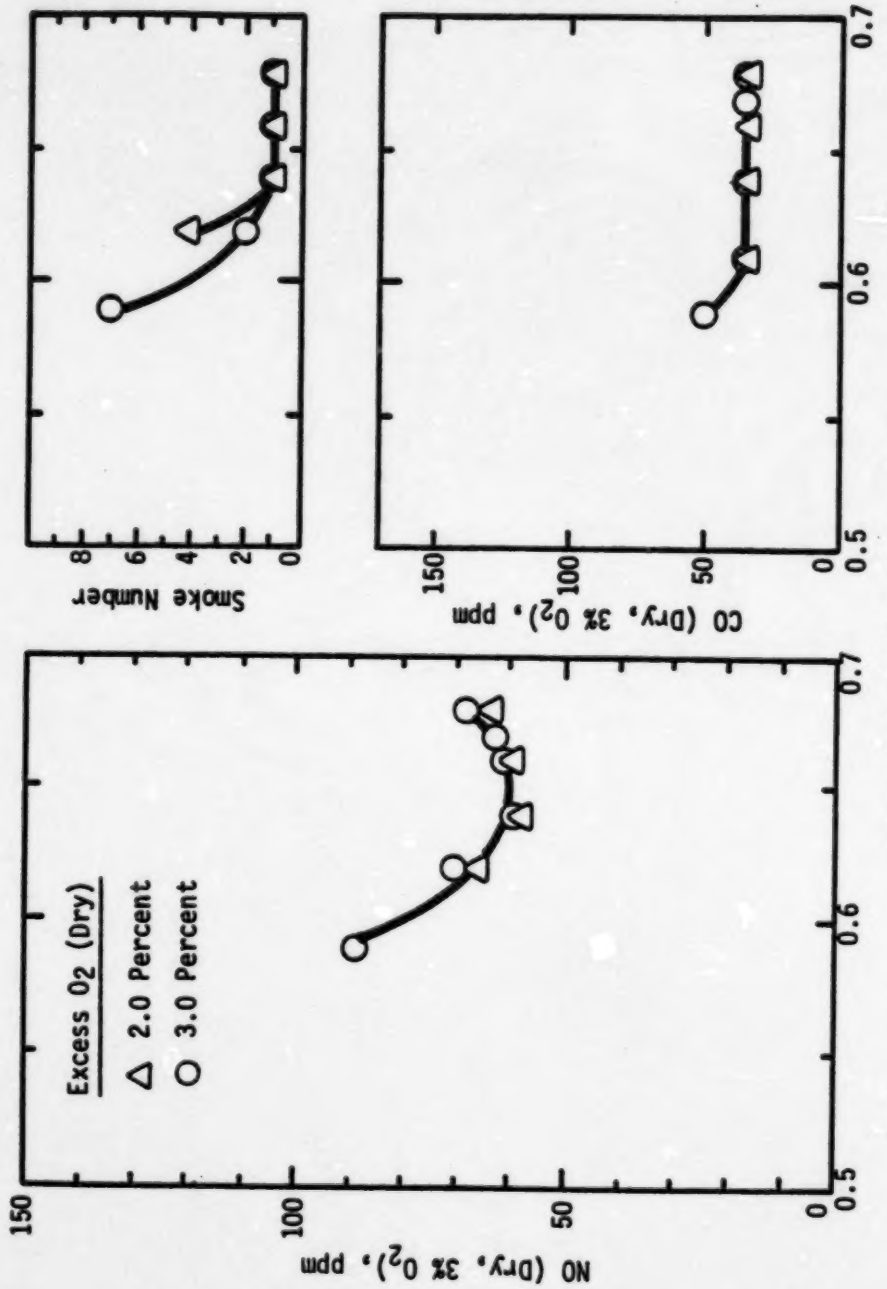


Figure 8. Field test results: NO, CO, and smoke emissions from steam generator with optimized burner configuration (54 x 10^6 Btu/hr).

Based on the results of the optimization tests, ideal operating conditions were programmed into the burner control system. A more detailed emissions characterization was performed at the optimum full-load operation point, including particulate mass loading, particulate size distribution, organic compounds, and manual (reference method) gas analyses, in addition to the normal continuous gas analyzers. Total particulate mass loading was determined by three separate methods (EPA method 5, cascade impactors, and modified EPA Source Assessment Sampling System). Results from a total of five measurements ranged from 23×10^3 to 46×10^3 micrograms per cubic meter (0.010 to 0.020 grains per dry standard cubic foot) of flue gas. This is very close to the level expected for quantitative conversion of ash in the fuel. Visual inspection of particulate catches indicated that no carbonaceous particulate was present. Figure 9 presents particulate size distribution for the optimum full-load operating condition. Most of the particulate is very fine, with approximately 65 percent below 1 micrometer.

Organic compound analysis has not been completed at this writing. Manual gas analyses by EPA Reference Methods were used to verify analytical methods, and compared favorably with the results of the continuous monitors.

Scaling and Application

Criteria developed in bench-scale and pilot-scale tests were applied to the design of the full-scale prototype low-NO_x burner. These criteria provide for (1) optimization of the fuel-rich first stage conditions for maximum conversion of fuel-bound nitrogen to N_2, and (2) optimization of second-stage conditions for mimimum thermal NO and smoke formation. The key design criteria (6) are:

1. Fuel Injection
   - High quality atomization.
   - Premixed fuel/air.
   - Minimal heat extraction to maximize fuel vaporization rate.
2. First-Stage Fuel-Rich Zone
   - Stoichiometric ratio approximately 0.7 to minimize TFN concentration.
   - Residence time in excess of 400 msec to allow sufficient TFN decay.
   - Control of heat loss to produce a first-stage temperature in excess of 2600°F to promote rapid conversion of fuel nitrogen fragments to molecular nitrogen.

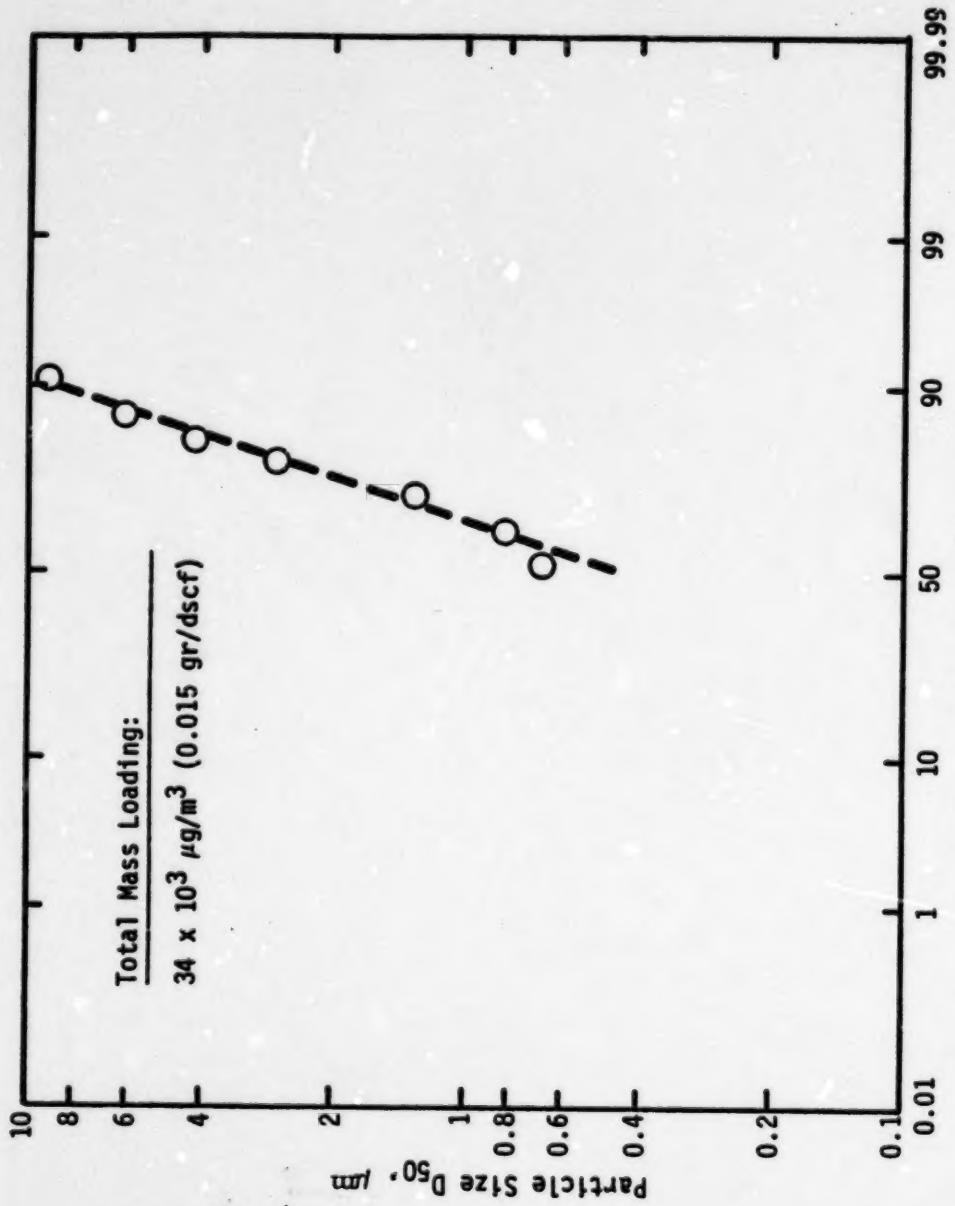


Figure 9. Field test results: Particulate size distribution (by cascade impactors) under optimum conditions.

3. Second-Stage Air Injection

- Partial quenching to minimize thermal NO formation in the second stage.
- Refractory choke to prevent backmixing and reduce heat loss.
- Intermediate to rapid second-stage mixing for minimizing smoke formation, and for control of flame shape.

Full-scale burner tests firing high nitrogen heavy oils in the experimental furnace and in the oilfield steam generator confirmed that the design criteria could be applied to full-scale hardware to produce the expected emissions results. Figure 10 compares NO_x emissions from bench-scale, pilot-scale, and full-scale tests versus first-stage residence time. The results represent a 750:1 range in scale. Below approximately 0.6 seconds NO_x emissions increase almost linearly with decreasing residence time. NO_x emissions from the tunnel furnace are slightly higher than the pilot-scale systems due to higher heat losses from the first stage associated with the smaller scale.

Data from the full-scale system indicate that increasing residence time above 0.6 seconds is less beneficial. This asymptotic behavior may indicate a shift in the controlling mechanisms from first stage processes to second stage processes at very low NO_x levels. Earlier pilot-scale tests (6) firing nitrogen-free fuels (distillate oil, propane) produced minimum NO_x levels of approximately 40 to 50 ppm from the optimized burner configuration, which was attributed to second-stage thermal NO_x formation. Although full-scale burner performance indicated that emissions exhibited some sensitivity to second-stage parameters (mixing, confinement), this sensitivity is much less severe than typically encountered in conventional systems, and the greatest impact is on flame shape.

Figure 11 compares NO_x emissions from the prototype burner to field test data (3) for conventional 50 x 10^6 Btu/hr steam generator burners and for other current NO_x control technology. Average NO_x emissions from conventional burners range from approximately 230 to 280 ppm over the range of excess air investigated in this work. By comparison, emissions from the prototype low-NO_x burner are approximately 65 ppm and insensitive to excess oxygen. This represents a 77 percent reduction over average NO_x emissions at 3 percent excess oxygen, without adverse impact on other pollutant emissions. Low-NO_x burner data from Reference 3 indicated that the main benefit of the burners tested was improved operability at low excess air levels. Recent low-NO_x burner technology (7) has shown that significantly reduced NO_x emissions can be achieved by delayed fuel/air mixing within the steam generator in combination with flue gas recirculation; however, the impact of the resulting flame conditions on furnace integrity has not been fully evaluated, and some low excess oxygen conditions can result in high CO and smoke emissions. NO_x reduction by postflame ammonia injection into the steam generator radiant section has produced NO_x emission levels (3) comparable to

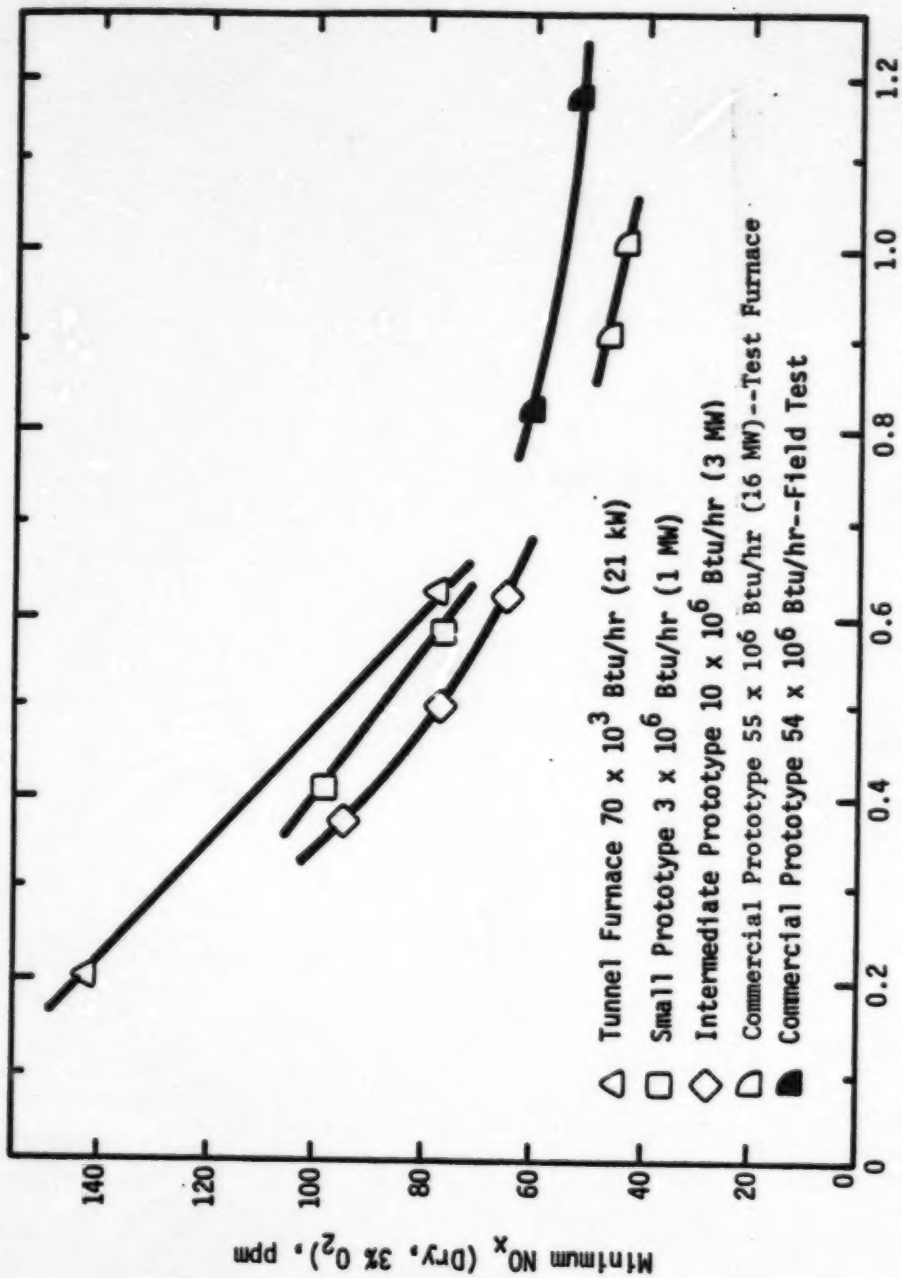


Figure 10. Comparison of NO_x emissions from bench-, pilot-, and full-scale prototype burner designs.

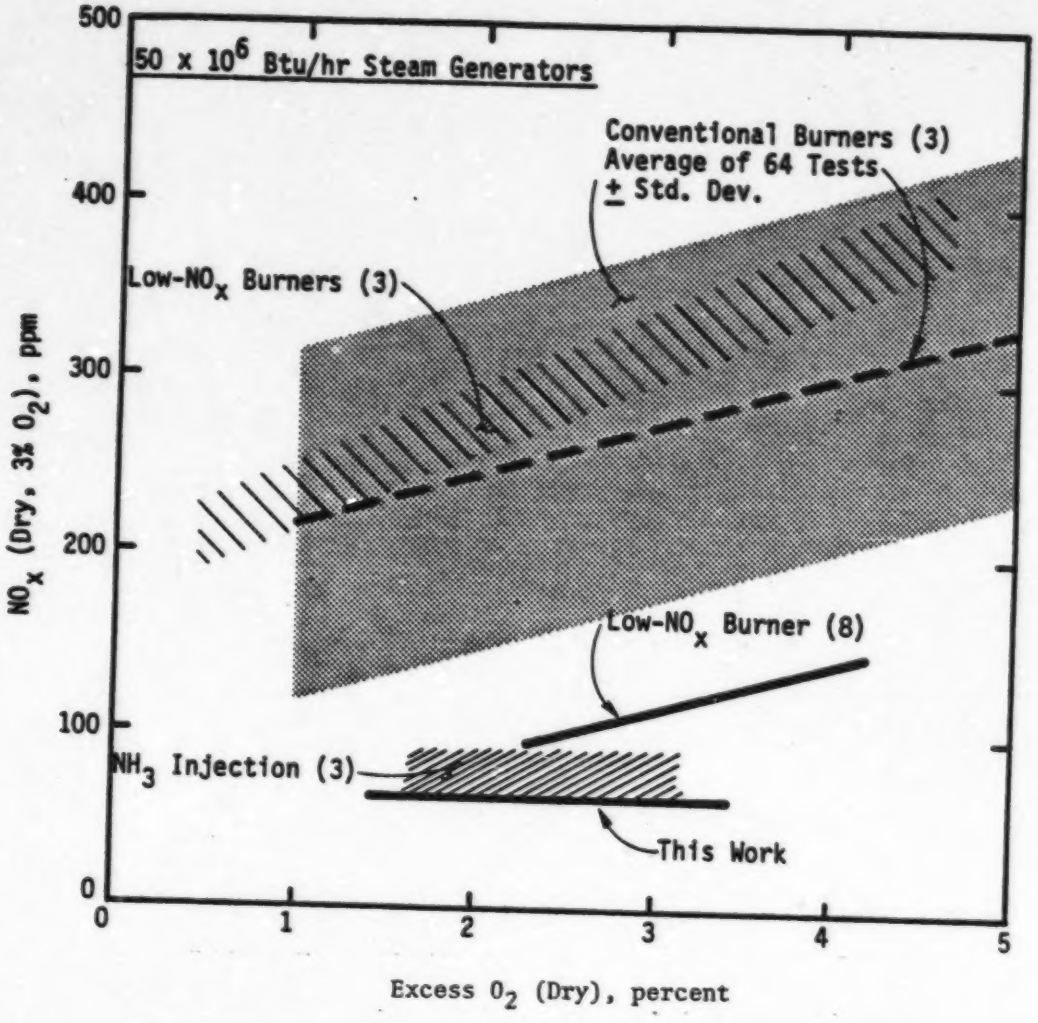


Figure 11. Comparison of prototype burner performance to conventional technology and current low-NO_x burner technology.

those achieved in this study. Test results indicated that it was difficult to maintain optimum ammonia injection conditions over extended periods because of changes in furnace heat transfer caused by tube fouling in the convective section. This could lead to NH_3 breakthrough or higher NO_x emissions. If the practical problems can be resolved these developing technologies may prove to be key to NO_x reduction.

The prototype low-NO_x burner described in this paper proves the applicability of the general design criteria developed in bench- and pilot-scale studies. Results of the 30-day burner evaluation currently in progress should determine what impact, if any, the burner will have on steamer performance and availability. Preliminary indications are very favorable and suggest that steam generator efficiency and lifetime factors will not be adversely affected.

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